CIVS
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STEEL MANUFACTURING SIMULATION SMSVC & VISUALIZATION CONSORTIUM

steelconsortium.org

ENABLING DIGITAL TECHNOLOGIES FOR IRON AND STEELMAKING PROCESSES

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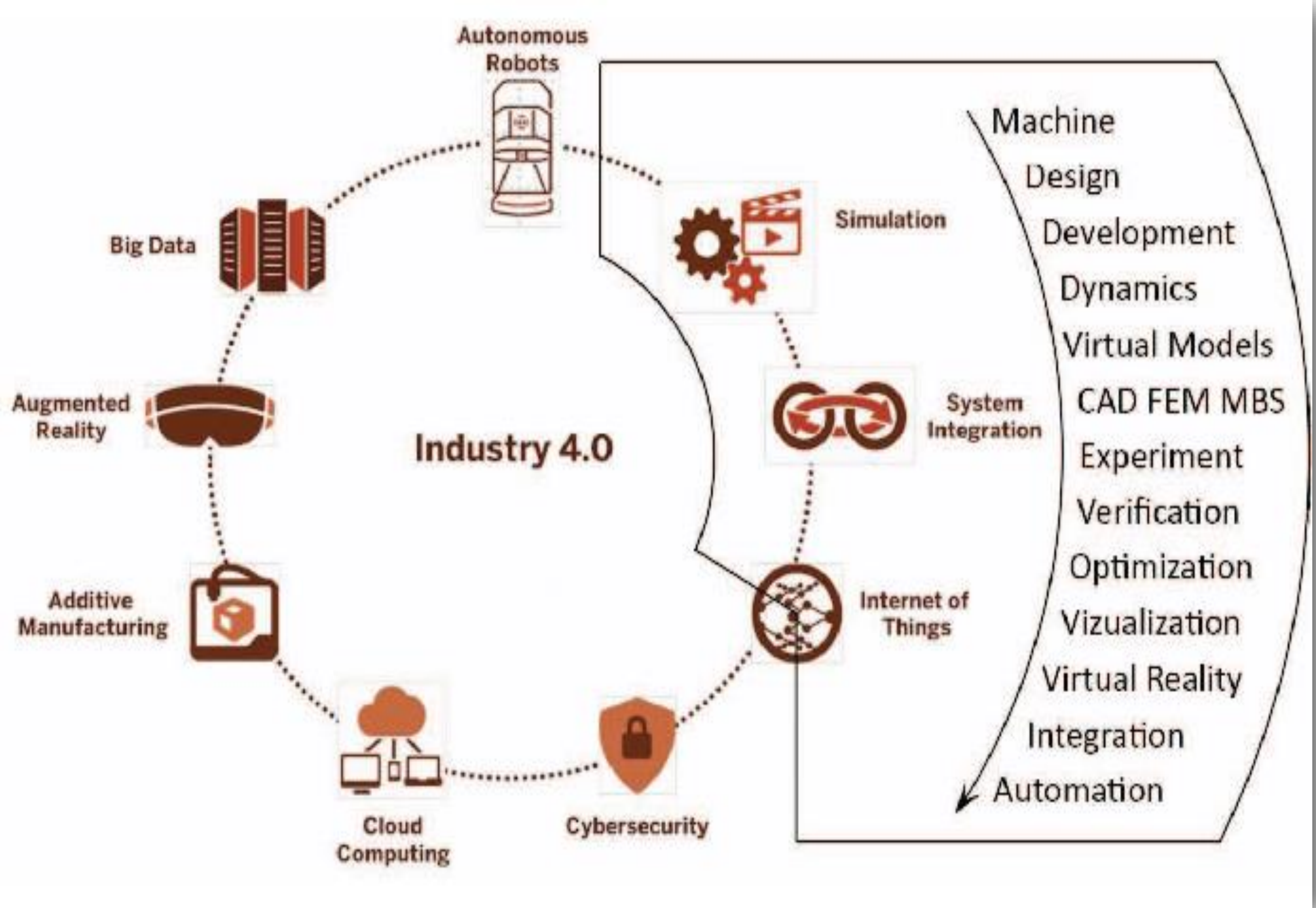
"Where Ideas Become Reality"

DIGITAL TRANSFORMATION



Jiri Kovar et. al., "Virtual Reality in Context of Industry 4.0", [2016 17th International Conference on Mechatronics - Mechatronika (ME)]

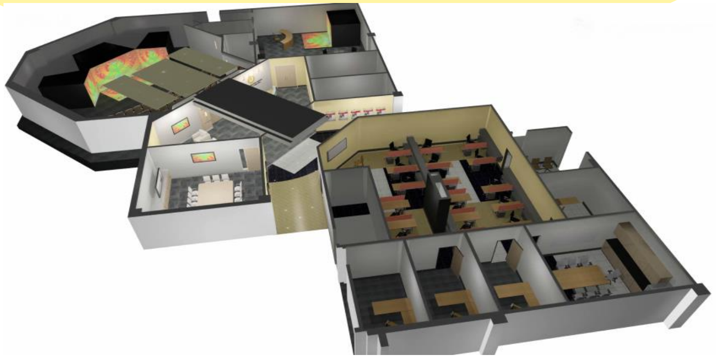
- **Simulation** such as **Computational Fluid Dynamics (CFD):** Physics-based predictions
- **Visualization (**VR & AR …): Effective communication and monitoring
- **High Performance Computing (HPC):** Accelerate computations
- **Machine Learning (ML):** Predictions based on historic data (a branch of Artificial Intelligence)
- **Digital Twin:** Virtual replicas of physical devices or processes

CIVS (since 2009) & SMSVC (since 2016)

PURDUE UNIVERSITY NORTHWEST · CIVS · SMSVC Steel Manufacturing Simulation & Visualization Consortium

Center for Innovation through Visualization and Simulation (CIVS)

- Missions
  - Innovation
  - Application (**$40+ million** savings from 5 out of 460+ projects)
  - Education
- Strategies
  - Integration of technologies
  - Application driven
  - Partnerships (**160+** organizations)



Steel Manufacturing Simulation and Visualization Consortium (SMSVC)

Research Areas

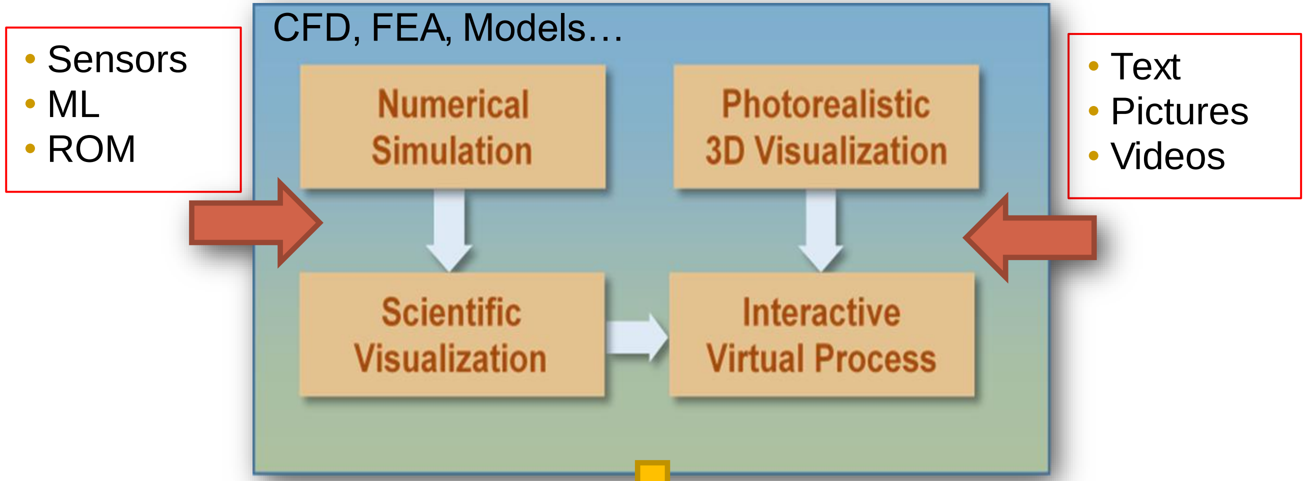
1) Energy Efficiency
2) Environmental Impacts
3) Operation Efficiency
4) Raw Materials Utilization
5) Reliability and Maintenance
6) Smart Manufacturing
7) Workforce Development
8) Workplace Safety

Project Examples

- Blast Furnace
- Electric Arc Furnace
- Caster Digital Twins
- Smart Ladle
- Spray Cooling Simulator
- Reheating Furnace
- Hydrogen combustion

ArcelorMittal · Charter Steel · Cliffs · EVRAZ · Gerdau · Linde · NiSource · NLMK USA · Nucor · SSAB · Steel Dynamics, Inc. · Stelco · Tata Steel · Union Gas · United States Steel

METHODOLOGY AND BENEFITS

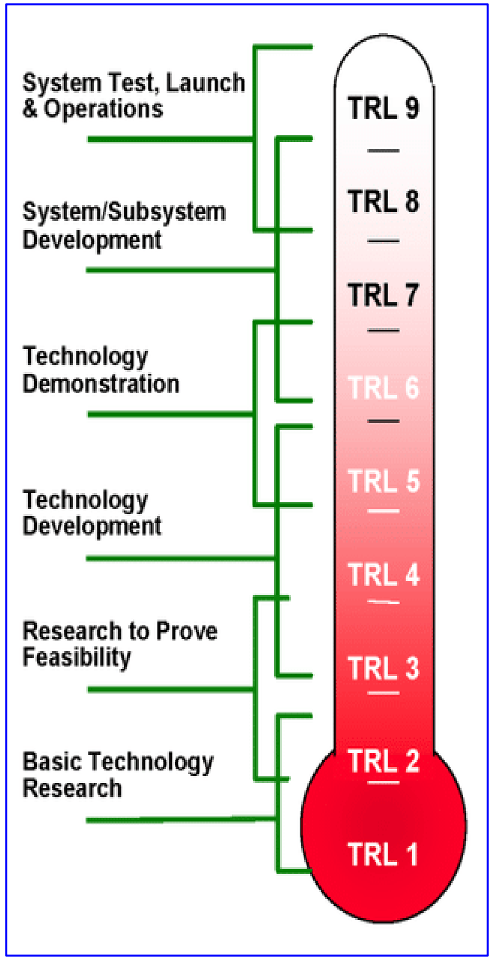


DIGITAL TWINS

- Off-line and online
- Multiple platform (VR, AR, PC, Mobile, Web)

Benefits

- **Insight:** visualizing flow fields
- **Foresight**: predict “future” or “what if”
- **Efficiency**: speed-up emerging & transformative technology R&D in all stages (TRL1 – 9*)

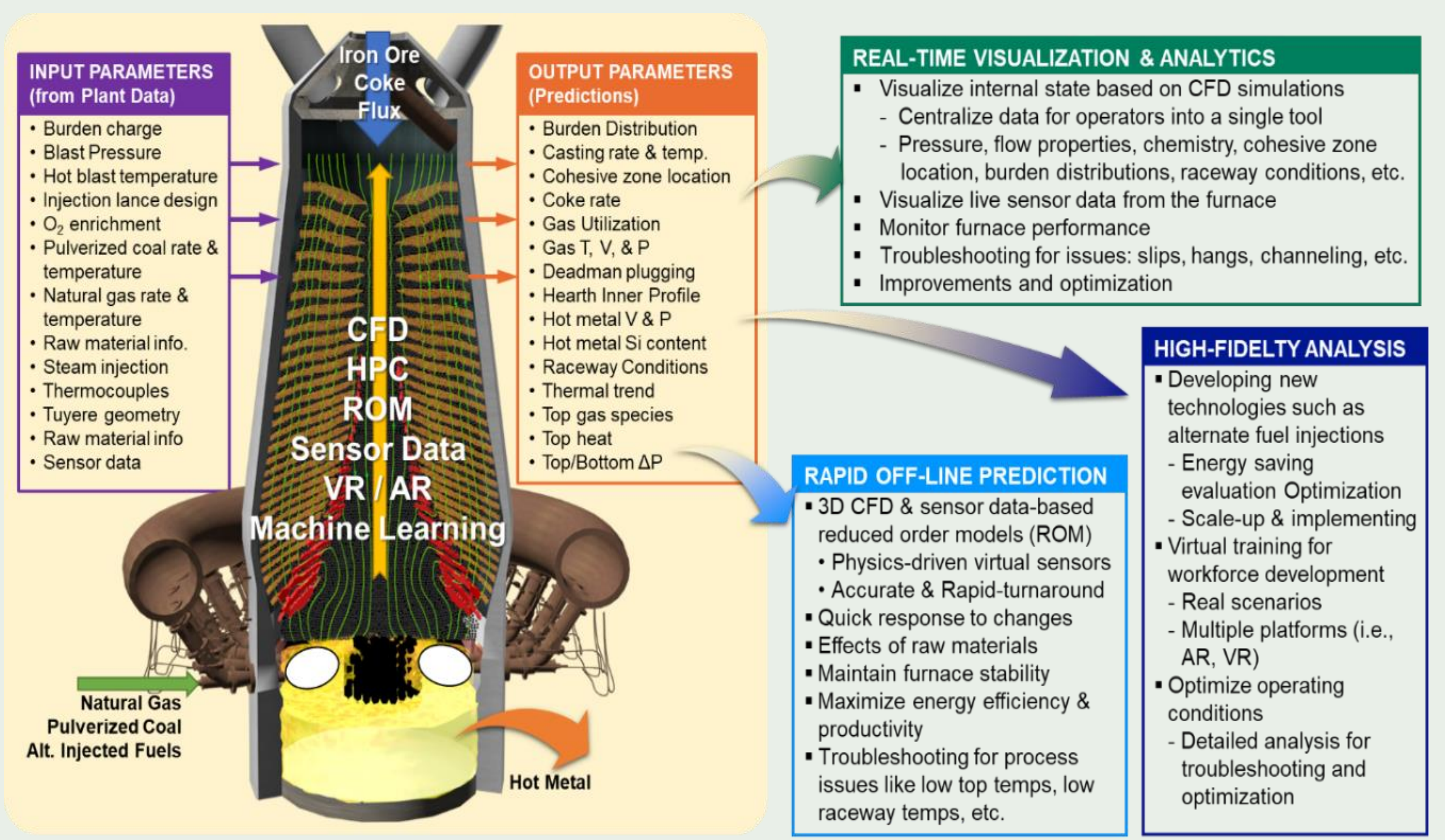


**Felici, Massimo. (2015). SECurity and trust COoRDination and enhanced collaboration Deliverable 6.3 Identification of Future Emerging Issues/Topics (Final Version).*

INTEGRATION OF DIGITAL TECHNOLOGIES

- **Efficient, effective, and economical**
  - Physics-based, data driven decisions
  - Lower risk & shorter cycle for developing and implementing transformative technologies
  - Real time monitoring and control
  - More effective training
  - Better communication

The IVBF Platform will be applicable for many other iron & steelmaking processes



A proposed **Next Generation Integrated Virtual Blast Furnace**
(led by Dr. Tyamo Okosun at PNW with industry, national lab, and universities)

VIRTUAL BLAST FURNACE

- **Issues:**
  - Energy efficiency
  - Pollutant Emissions
  - Campaign life
  - Downtime
  - Training
- **Major Outcomes (since 2002):**
  - Virtual blast furnaces used for
    - Design
    - Troubleshooting
    - Optimization
    - Scale-up
    - Training
  - Improvement of energy efficiency and emissions
  - Downtime reduction
- **Sponsors and Partners:**
  - AIST, AISI, ArcelorMittal, Cleveland-Cliffs, DOE, Stelco, SMSVC, Tata Steel, Union Gas, and U.S. Steel

CFD + FEA + HPC + Visualization

Carbon Footprint Impact

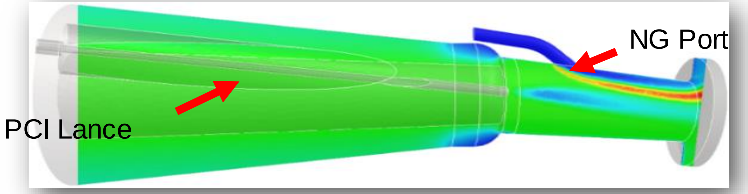
- For 4.5% energy savings, around 120,000 tons of CO_2/year reduction per a typical blast furnace (BF)
- For 10% energy savings, around 260,000 tons of CO_2/year reduction per a typical BF and 4.5 million tons of CO_2/year reduction across the entire U.S. steel industry

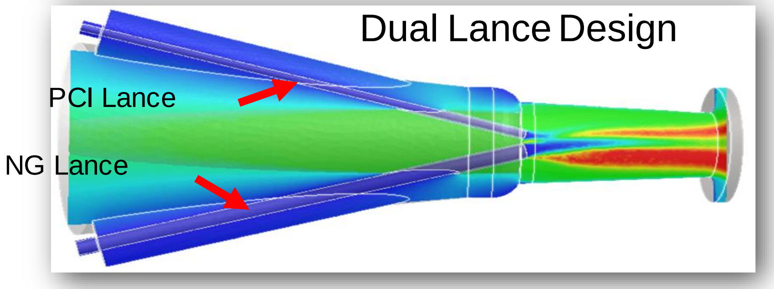
OUTCOME EXAMPLES

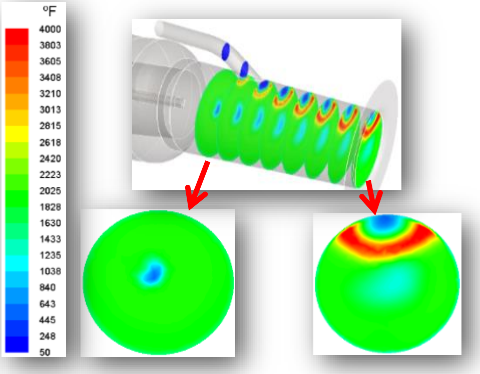
Cleveland-Cliffs Blast Furnaces

- **Design**: Implemented dual lance design - increased coal combustion efficiency by **25%**
- **Optimization:** Potential improvement of **2.5%** productivity using NG as PCI carrier gas
- **Troubleshooting**: Identified causes of tuyere failures

Baseline Design



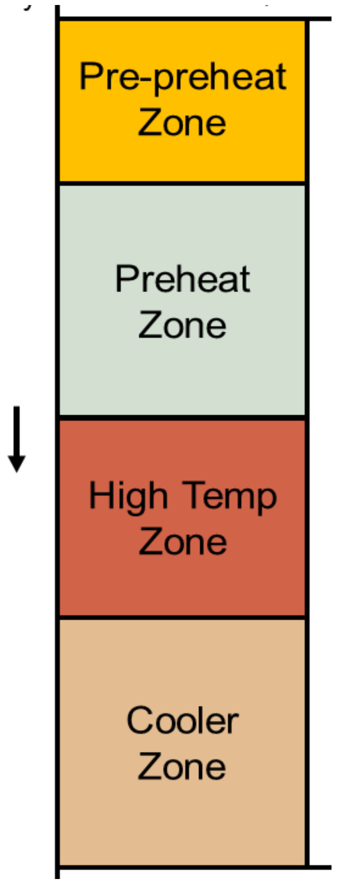


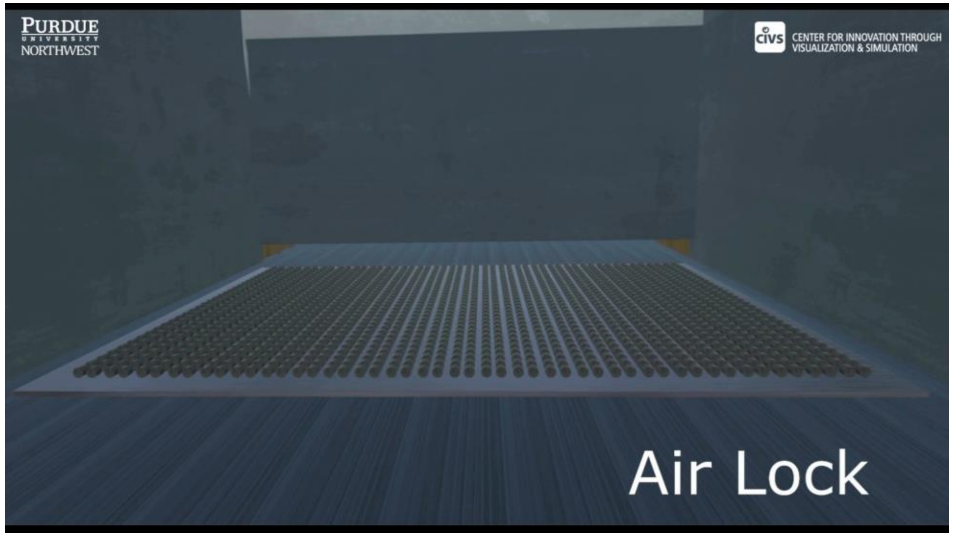


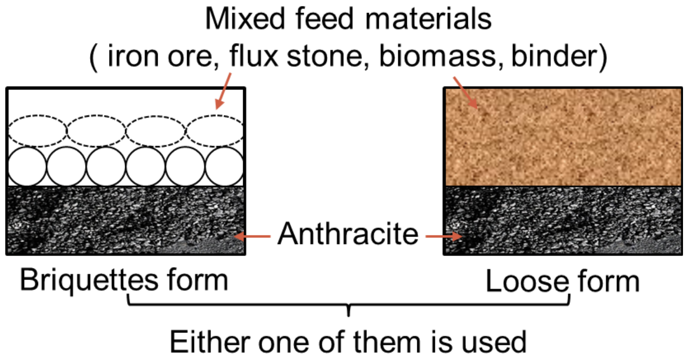
- **H_2 Injection**
  - Reduce CO_2
  - instability due to quenching effect
- **Premixed NG + H_2**
  - Boost H_2 rate
  - Balance injections to achieve desired flame T and coke rate with lower CO_2
- **Preheated H_2 Injection**
- **Preliminary results:**
  - Fundamental understandings
  - Highest stable injection rates
  - Quantitative correlations

E-IRON NUGGET PROCESS SCALE-UP

- **Process:**
  - A novel iron smelting process developed by Carbontec Energy Corporation (CarbonTec) to utilize biomass to replace coke
    - To produce high quality pig iron nuggets
    - To significantly reduce CO_2 emissions
- **Objective (12 months):**
  - Utilizing High Performance Computing (HPC) Computational Fluid Dynamics (CFD) simulations to guide furnace designs for the E-Iron™ Nugget process



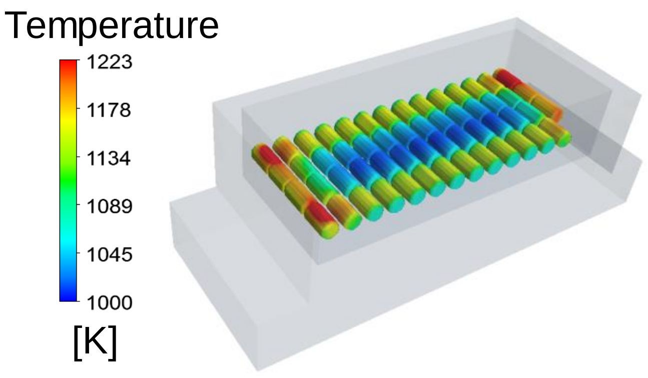


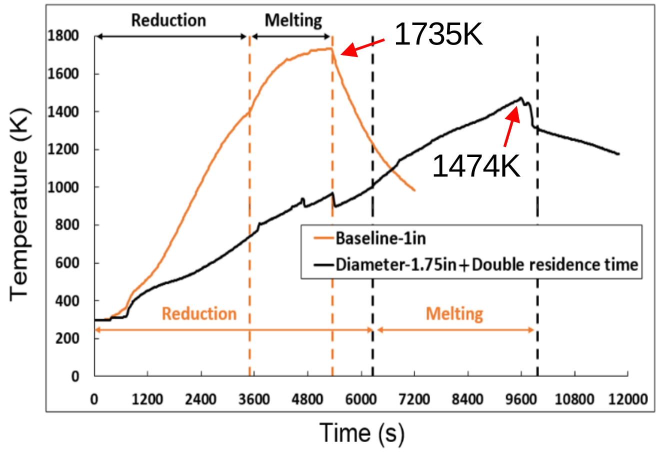


Mixing iron ore or steel mill wastes with renewable biomass and a lime flux to produce a self-reducing pellet

PROJECT OUTCOMES

- **Research and development (TRL 4&5):**
  - Developed CFD Models for predicting the success or failure of iron reduction and nugget formation (13 reactions)
  - Validated with **pilot scale data** with 4 cases (diff. < 5%)
- **Scale-up (commercialization demonstration) (TRL 7&8)**
  - Recommendations for the final design of the production scale furnace (100,000 tonnes/yr.)
  - 15 iterations with 6 variables: temperatures in preheating, reduction, and melting zones; residence time in reduction & melting zones; and briquette size
- **Visualization**
  - Visualization of a plant in operation
  - CFD data integrated to show process details and highlight ways to increase production and lower production costs.
- **Benefits:**
  - CFD simulations verified the technology, provided better understanding, and assisted in the final design to avoid pitfalls
  - Visualization helped for marketing and convincing investors
  - Three lines (100,000 tonnes/year/line) to be built in Burns Harbor, Indiana





HIGH PERFOMANCE COMPUTING

- Benefits: Speed up computational time with more details
- HPC availability: national labs, universities, companies, & cloud
- **DOE AMO HPC for Manufacturing (HPC4Mfg) Program**
  - Two regular solicitations annually, fall & spring
  - Eligibility: U.S. manufacturers
  - Submission: 1) concept paper; 2) full proposal
  - Budget: $300,000 for phase 1 to support computing cycles and work performed by National Labs, universities, and non-profit partners.
  - Cost share: 20% from industry
  - National Labs: LLNL, ANL, ORNL
  - PNW CIVS & SMSVC Role:
    - Subcontractor of national labs
    - Participated in 6 projects

Example

Utilizing HPC to Model the E-Iron Nugget

- CarbonTec
  - Principal Investigator to submit proposals and sign CRADA with LLNL
  - Provide geometry and operating conditions
  - Implement results
- LLNL
  - HPC facility
  - Selection of experimental data for validation
  - Verification of chemical kinetics
  - Review models and results
- PNW CIVS
  - Subcontractor from LLNL
  - Developed and validated CFD Models
  - Run CFD simulations on LLNL cluster
  - Create visualization simulators

DIGITAL TECHNOLOGIES TO ACCELERATE DEVELOPMENT PROCESS

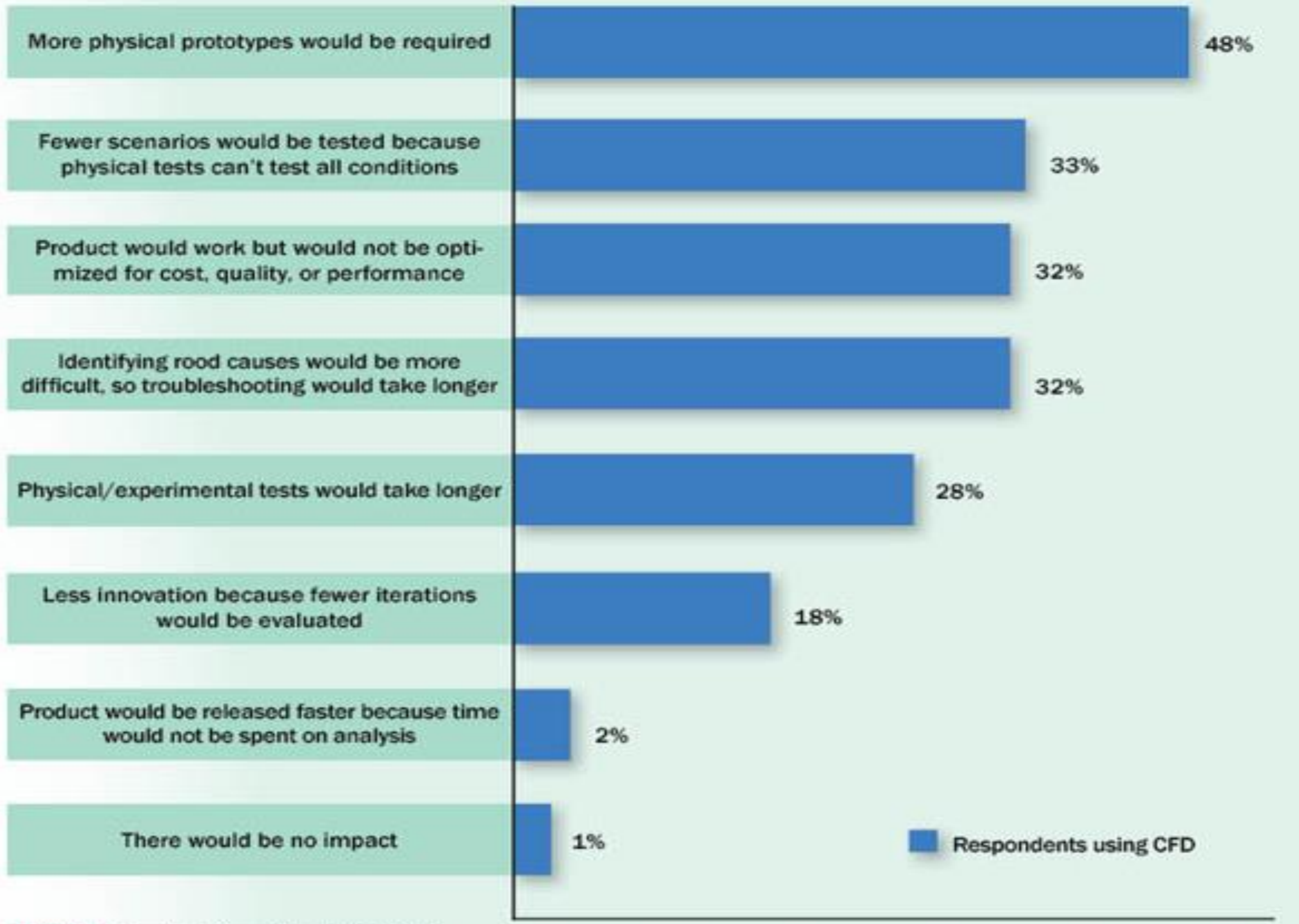
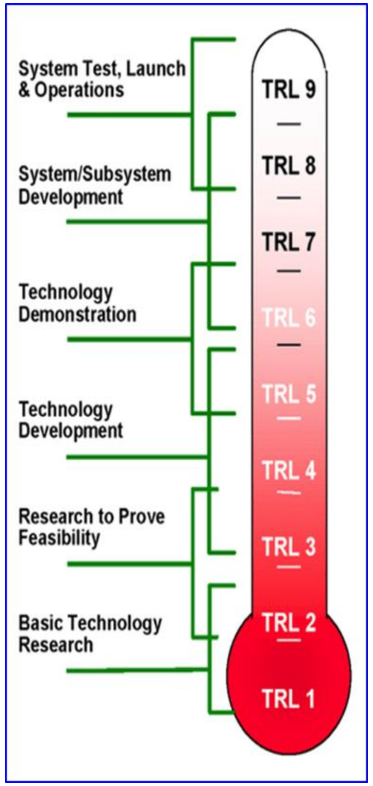


FIGURE 2: Leading Impacts of Not Using CFD Source: *Aberdeen Group, April 2011*

https://www.digitalengineering247.com/article/the-role-of-cfd-in-product-development/

DIGITAL TECHNOLOGIES TO ACCELERATE DEVELOPMENT PROCESS

- **TRL 2:** Technology concept formulated **(CFD) -** Refine new concept, evaluate feasibility
- **TRL 3:** Experimental proof of concept **(CFD) -** Complementary to lab scale prototype, identify key parameters, verification of the proof of concept
- **TRL 4:** Technology validated in lab **(CFD) -** Complementary to small-scale prototype integrated with complementing subsystems, validation of the new technology
- **TRL 5:** Technology validated in relevant environment **(CFD, Visualization) -** Complementary to large scale prototype integrated with supporting components, assess parameters for scale-up
- **TRL 6:** Technology pilot demonstrated in relevant environment **(CFD, Visualization) -** Assist in demonstrating the technology as fine-tuned to a variety of operating conditions in relevant environment.
- **TRL 7:** System prototype demonstration in operational environment **(CFD, Visualization, Process Modeling) -** Assist in demonstrating full scale pre-commercial system is demonstrated in operational environment, verify and validate the integration of upstream and downstream technologies
- **TRL 8:** System complete and qualified **(CFD, Visualization, Process Modeling, ML, ROM, Digital Twins) -** Assist in finalizing the technology for deployment and stable operation, training and maintenance documentation, and integration at system level
- **TRL 9:** System proven in an operational environment **(CFD, Visualization, Process Modeling, ML, ROM, Digital Twins) -** Assist in proving the technology fully operational and ready to be commercialized, system optimization for full-rate production.



CHALLENGES AND OPPORTUNITIES

- Culture evolution
- Connection to practical, real-world applications
- Physics-based, data driven, rapid predictions
- Big data (quality and completeness)
- Model validations
- Integration
- Collaboration
- Workforce development

Advanced digital technology plays a key role in developing transformational technologies for Zero-emission Ion-and Steelmaking!

FUTURE STEELMAKING

AR/VR Visualization

Simulation

Modeling

- INDUSTRY 4.0
- SMART STEEL MANUFACTURING
- DIGITAL TRANSFORMATION

HPC

ML

Sensors

Big Data

Cloud

IoT

Cybersecurity

THANK YOU!

- All the government funding agencies
- All the company sponsors
- All the collaborators
- SMSVC member companies
- CIVS faculty, staff, and students

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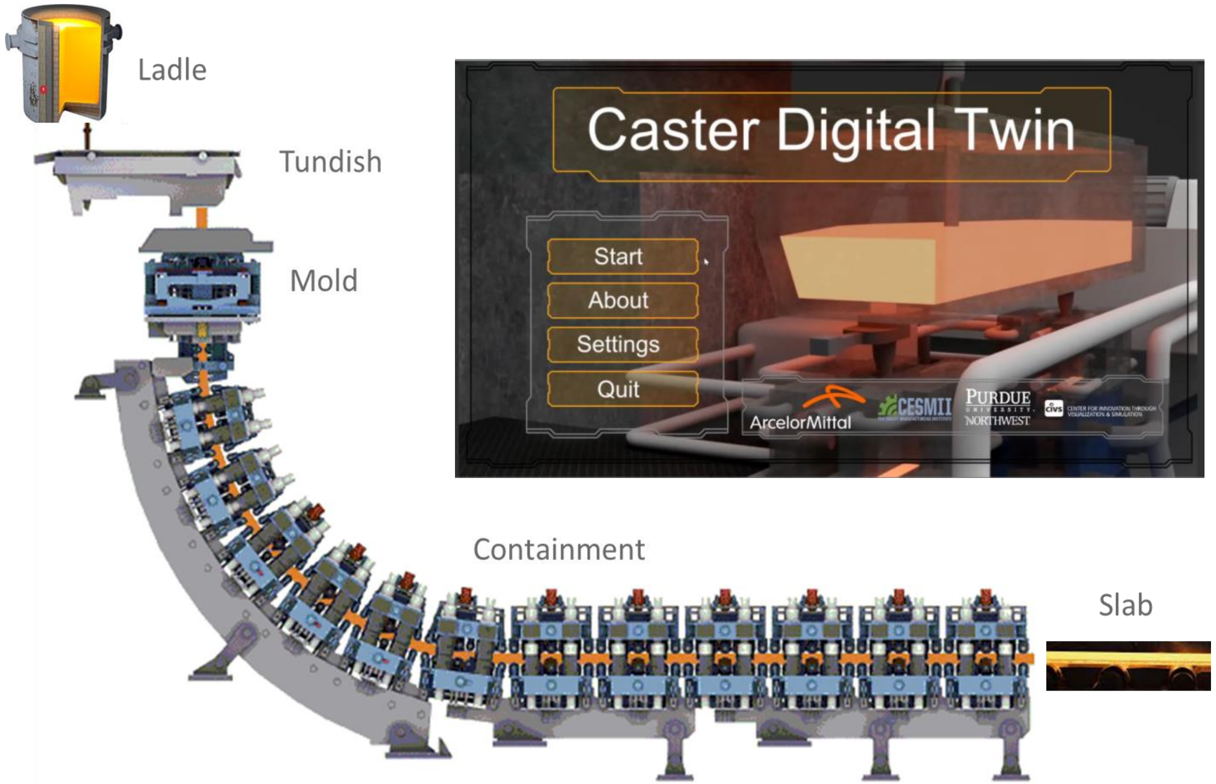
3-D CASTER DIGITAL TWIN

- **Objective:** To develop and deploy 3-D digital twin of a continuous casting process for producing steel slabs both offline and online
  - Track casting parameters relevant to slab quality
  - Track equipment, sensor and modeling parameters relevant to machine condition
- **Sponsor & Partners:** CESMII, Arcelormittal, Cleveland-Cliffs, PNW

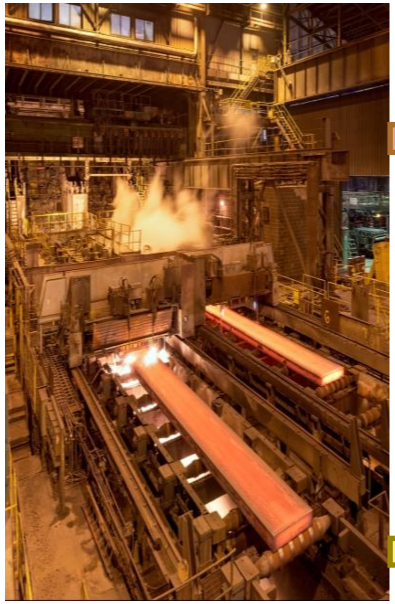


Penn, Johann; Pennerstorfer, Paul; Jungbauer, Andreas. "New Generation of Continuous Casting Plants with Intelligent Manufacturing Strategy" BHM Berg- und Hüttenmännische Monatshefte 11 Vol. 1632018; SN - 1613-7531; UR - https://doi.org/10.1007/s00501-017-0694-4

Digital Twin

- Digital replica of an actual physical caster
- Track important aspects of a process real-time and retrospectively
- Integration of real-time sensor-generated data, IoT, physics-based models (e.g. CFD), AI, machine learning and software analytics with 3D graphics tools
- Continuously update and change during operation
- Feedback to the control system

PROTOTYPE CASTER DIGITAL TWIN

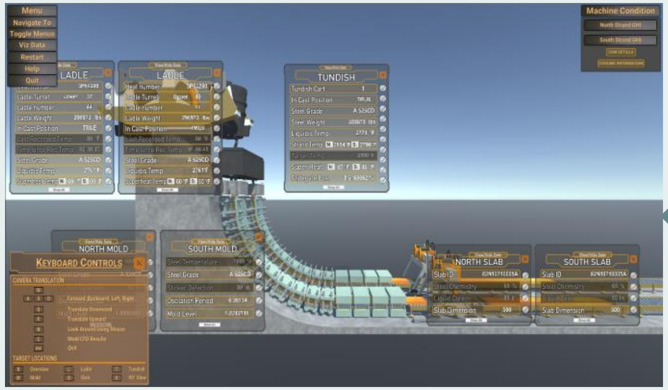


OPERATING CONDITIONS

- Heat number
- Steel grade
- Casting speed, spray distribution
- Ladle weight
- Superheat

SENSOR DATA

- Bearing cooling
- Mold cooling
- Machine Cooling



MODEL DATA

- Sarclad data
- Slab quality tracking (GCM, CSQ, Dimensions
- CFD

VISUALIZATION

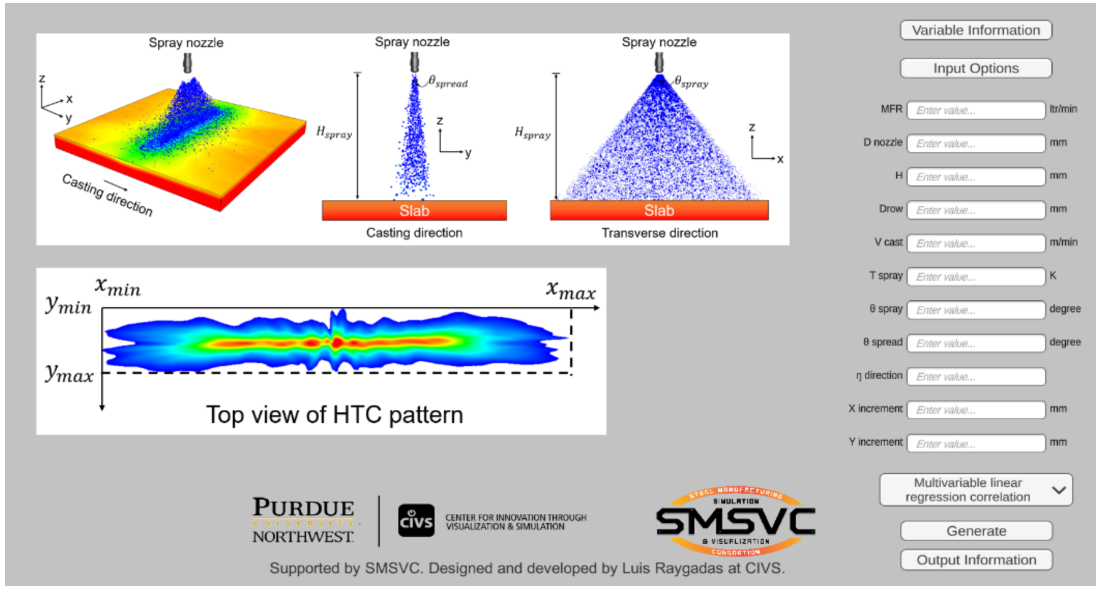
- Caster Health Monitor
- Off-line data stepping
- Sarclad data graphical display

CASTER OPERATION

- Operators and engineers
- Caster control room
- Maintenance

DYNAMIC SPRAY COOLING CONTROL

- **Motivations:**
  - Dynamic control of spray water rate for continuous casting is critical to enhance steel strength.
  - Heat transfer coefficient (HTC) distribution under each nozzle is required as boundary condition.
  - HTC is often correlated with nozzle parameters & operating conditions.
  - Experiment-based correlation development is labor-intense & expensive.
- **HTC Predictor**:
  - Multi-selection of HTC correlations
  - Customizable correlation coefficients based on a specific caster



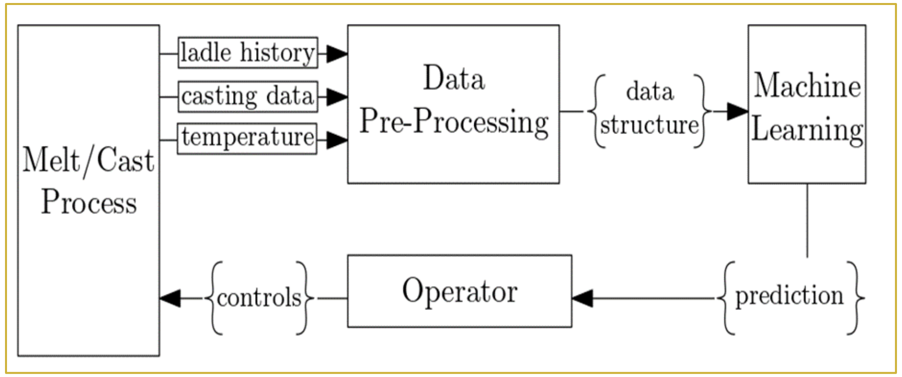
Step 1 Conditions → Step 2 High-fidelity CFD simulation → Step 3 HTC correlation → Step 4 HTC Predictor

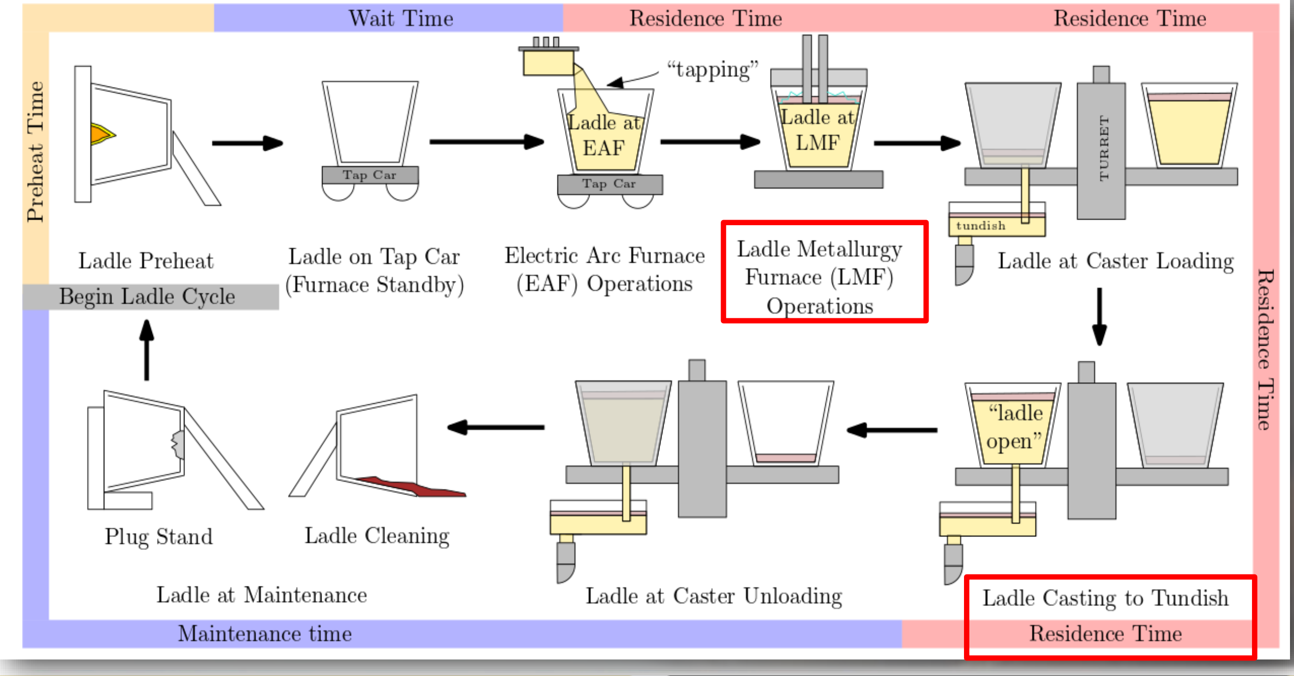
Applications

- On-line real-time dynamic spray control
- Off-line/on-line malfunctioning nozzle identification
- Off-line nozzle selection
- Off-line researcher/operator training

SMART LADLE

- **Process:** Ladle is used for transporting liquid steel from EAF or BOF to caster and for steel refining
- **Current Issue:** Casting temperature control by adjusting LMF temperature by operator experience
- **Objectives**:
  - To develop an AI tool for ladle operation
    - To accurately correlate casting temperature with known input variable conditions
    - To improve operational responses for casting temperature control
  - To develop generalized procedures for applying deep learning to other steelmaking processes
- **Impacts:**
  - Consistent casting quality
  - Increased productivity and energy efficiency
- **Sponsors:** AIST & SMSVC





SMART LADLE ON-SITE IMPLEMENTATION

Example

- Steel Dynamics, Inc. Butler Division, IN
- Integrated with on-site production database for operator control interface
- Accuracy of predictions meets industry needs
  - Current average error of **3°F,** which is better than desired (5°F)